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Robert D. Ingebo
Lewis Research Center
Cleveland, Ohio

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FUEL SPRAY SIMULATION WITH TWO-FLUID NOZZLES

Robert D. Ingebo
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

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Abstract

Two-phase interacting flow inside a two-fluid fuel atomizer was investigated and a correlation of aerodynamic and liquid-surface forces with characteristic drop diameter was obtained for liquid-jet breakup in Mach 1 gasflow. Nitrogen gas mass-flux was varied from 6 to 50 g/cm^2 sec by using four differently sized two-fluid atomizers with nozzle diameters varying from 0.32 to 0.56 cm. The correlation was derived by using acoustic gas velocity, V_c, as a basic parameter in defining and evaluating the dimensionless product of the Weber and Reynolds numbers as follows: $WeRe = \rho_g^2 D_o^2 V_c^3/\mu_l \sigma$ where ρ_g is gas density, D_o is liquid-flow orifice diameter, V_c is the acoustic velocity of the gas, μ_l is the liquid viscosity and σ is the liquid surface tension. By using the definition of WeRe given above, it was found that the ratio of orifice diameter to Sauter mean drop diameter, D_o/D_{32}, could be correlated with the dimensionless ratio WeRe and the gas to liquid density ratio, ρ_g/ρ_l, as follows:

$$D_o/D_{32} = 8\ [(\rho_g/\rho_l)WeRe]^{0.44}$$

From this expression, it is evident that $D_{32} \sim V_c^{-1.33}$ which agrees very well with atomization theory for the case of acceleration-wave breakup of liquid jets.

Nomenclature

- b — dropsize parameter in Nukiyama-Tanasawa expression, cm
- c — dropsize parameter in Rosin-Rammler expression, cm
- D_c — characteristic drop diameter measured for entire spray, cm
- D_i — diameter of ith drop, cm
- $D_{v.5}$ — volume median drop diameter, cm
- D_{31} — volume-linear mean drop diameter, $\left[\sum_i nD_i^3/\sum_i nD_i\right]^{0.5}$, cm
- D_{32} — Sauter mean drop diameter, $\sum_i nD_i^3/\sum_i nD_i^2$, cm
- N_n — exponent for Nukiyama-Tanasawa dropsize distribution expression
- N_r — exponent for Rosin-Rammler dropsize distribution expression
- n — number of droplets
- Re — Reynolds number, $D_o\rho V/\mu$
- V — fluid velocity, cm/sec
- v — volume fraction of droplets with diameters less than or equal to x
- W — weight flow of fluid, g/sec
- We — Weber number, $D_o\rho V^2/\sigma$
- x — droplet diameter in dropsize distribution expression, cm
- μ — absolute viscosity, g/cm sec
- ρ — fluid density, g/cm^3
- σ — surface tension of liquid relative to air, dynes/cm

Subscripts:

- c — acoustic
- g — gas
- l — liquid
- n — nitrogen gas
- o — orifice
- r — relative
- w — water

Introduction

An experimental investigation of interacting aerodynamic and liquid-surface forces was conducted to determine the effect of two dimensionless force ratios, i.e., Weber and Reynolds numbers, on the characteristic dropsize of sprays produced by atomizing small-diameter liquid jets in high-velocity gasflow. Such information is needed to better understand the breakup of liquid fuel jets in rocket and jet engines. The present study was conducted primarily in the aerodynamic-stripping regime at Mach 1 gasflow.

When liquid fuels are injected into gas turbine or rocket combustors they are rapidly atomized into clouds of vaporizing droplets that quickly ignite and burn. To accurately describe the fuel-spray combustion process, detailed knowledge of fuel spray formation is required and characteristic dropsize measurements are needed at the point of initial spray formation near the atomizer orifice. Also, to better understand how liquid fuels are atomized, mathematical expressions are needed that adequately describe processes such as two-fluid atomization in which various liquid and gas combinations may be used to produce the sprays. To do this, the effects of liquid and gas properties on spray dropsize must be determined. Numerous investigators have reported experimental results that correlate spray characteristic dropsize with relative velocity, i.e., gas velocity relative to liquid-surface velocity, and also with liquid properties as given in Refs. 1 to 5. Some of the correlations agree very well with atomization theory whereas others differ considerably. This could be attributed to the fact that measurement techniques and instrumentation have not yet been sufficiently developed or standardized to such an extent that good agreement might be expected. Experimental studies are needed that will produce correlations of characteristic dropsize measurements with dimensionless force ratios such as the Reynolds and Weber numbers. Such correlations are very useful in calibrating fuel nozzles for jet engines. This can be accomplished by first making dropsize measurements of water sprays produced with the fuel nozzle and then using the correlation to correct for the effects of liquid density, viscosity, and surface tension on the dropsize that would be produced with the nozzle using a fuel such as a Jet-A.

Prior to the present study, an investigation was conducted with two-fluid atomizers and good agreement of experimental results with atomization theory was obtained, as discussed in Ref. 6. It was found that the Sauter mean drop diameter, D_{32}, could be correlated with nitrogen gas flowrate, W_n, raised to the -1.33 power, which agrees well with atomization theory for liquid jet breakup in high-velocity gasflow. As a continuation of that study, the present investigation was initiated to extend experimental conditions to include a variation in the nozzle orifice diameter. By using four differently sized atomizers, it was possible to investigate the effects of nitrogen gas mass-flux, ρgVg, on the characteristic drop size, Dc, of the sprays. Values of ρgVg were calculated from nitrogen gas weight flow per unit area, W_n/A_o, and values of A_o for the four different nozzle orifices varied from 0.0804 to 0.246 cm^2. By further analysis of the data, it was possible to describe the atomization process in terms of the effect of dimensionless force ratios, i.e., Weber and Reynolds numbers, on characteristic dropsize, D_c, at Mach 1 gasflow conditions.

From a study reported in Ref. 6, it was found that the effect of droplet vaporization on spray samples could be minimized by taking the sample at a distance of only 2.2 cm downstream of the atomizer orifice. This technique gave the best agreement between theoretical and experimental effects of nitrogen gas flowrate on Sauter mean, D_{32}, volume-linear mean, D_{31}, and volume median, $D_{v.5}$, dropsizes. Therefore in the present study, characteristic drop diameters were measured at a sampling distance of 2.2 cm downstream of the nozzle orifice, with a scattered-light scanning dropsize measuring instrument previously developed at the NASA Lewis Research Center. Exponents for both the Rosin-Rammler and the Nukiyama dropsize distribution expressions were also obtained with the scattered-light scanner. All of the sprays were injected into low-velocity, 5 m/sec, airflow to aid in transporting very small droplets through the laser beam. Liquid and gas pressures were varied over a range of 0.2 to 1.0 MPa.

Apparatus And Procedure

The atomizer, mounted in the open duct, and the auxiliary equipment are shown in Fig. 1. Air, supplied at ambient temperature, 293 K, passed through the 24 cm inside diameter test section then exhausted to the atmosphere. The test section was 1 m in length and a 5.08 cm diameter orifice was used to measure airflow rate in the test section. With a control valve, an airstream velocity of 5 m/sec was maintained in the test section to aid in transporting small droplets through the laser beam. A schematic drawing of the spray and instrumentation is illustrated in Fig. 2.

To study liquid-jet break-up, four pneumatic two-fluid atomizers with orifice diameters ranging from 0.32 to 0.56 cm were used to produce clouds of small droplets. The atomizer, illustrated in Fig. 3 as mounted at the center line of 24 cm diameter duct and operated over pressure ranges of 0.2 to 1.0 MPa for both water and nitrogen gas. Water sprays were injected downstream into the airflow just upstream of the duct exit. The sprays were sampled at a distance of 2.2 cm downstream of the atomizer orifice with a 7.5 cm diameter laser beam.

Water at a temperature of 293 K, measured with an I.C. thermocouple, was axially injected into the airstream by gradually opening a control valve until the desired flow rate was obtained as indicated by a turbine flowmeter. Nitrogen gas was then turned on to atomize the water jet and weight flowrate was measured with a 0.51 cm diameter sharp-edge orifice. After air, nitrogen, and water flowrates were set, the Sauter mean, volume median, and volume-linear drop diameters were measured with the scattered-light scanner to characterize the sprays. Exponents for the Rosin-Rammler and Nukiyama-Tanasawa dropsize distribution expressions were also determined using the scattered-light scanner. The optical components are shown in Fig. 2. They consist of a 1 mW helium-neon laser, a 0.003-cm-diameter aperture, a 7.5-cm-diameter collimating lens, a 10-cm-diameter converging lens, a 5-cm-diameter collecting lens, a scanning disk with a 0.05-cm-slit, a timing light, and a photomultiplier detector.

The spatial resolution of the scattered-light scanner is 2.86 cm and corresponds to the laser beam diameter. A sufficient volume of each spray, was sampled capture the entire spray. The effect of dropsize distribution functions on scattered-light scanner measurements is discussed in detail in Ref. 7. Very briefly, it was found in Ref. 7 that the irradiance distribution is only weakly related to the particle diameter distribution function; therefore, the irradiance distribution was used to determine characteristic drop diameters and changes in the drop size distribution function were assumed to have a negligible effect on drop size measurements made with the scattered-light scanner. Reproducibility tests gave experimental measurements of dropsize that agreed within ±5 percent. Five sets of monosized polystyrene spheres having diameters of 8, 12, 25, 50, and 100 μm, were used to calibrate the scattered-light scanner. A more complete description of the scattered-light scanner can be found in Refs. 7 and 8.

Experimental Results

Atomization of liquid jets in high-velocity gasflow was studied to determine the effect of Weber and Reynolds numbers on characteristic dropsize. Measurements of three different characteristic drop diameters were made 2.2 cm downstream of the atomizer and correlated with nitrogen gas flowrate, W_g. The effect of atomizer orifice-area on characteristic dropsize was then determined from dropsize data obtained from the four atomizers. Reynolds and Weber numbers for the sprays were related to the following characteristic dropsizes: Sauter mean, D_{32}, volume median, $D_{v.5}$, and volume-linear mean, D_{31}, drop diameters.

Effect of Gas Flowrate, W_g, on Characteristic Dropsize

In Fig. 4, the reciprocal of the Sauter mean drop diameter D_{32} is plotted versus nitrogen gas flowrate, W_g, and the following relationship is obtained for the four atomizers:

$$D_{32}^{-1} \sim W_g^{1.33} \tag{1}$$

at a water flowrate of 3.15 g/sec and at a distance of 2.2 cm downstream of the atomizer orifice. The entire spray was sampled using the scattered-light scanner. It is evident from the plot that at a given nitrogen gas flowrate the surface area/unit volume of spray, or D_{32}^{-1}, was lower for atomizers having larger orifice diameters. This was expected since mass flux also varies inversely with orifice diameter or orifice area.

Measurements of the volume median $D_{v.5}$, and volume-linear, D_{31}, drop diameters were also obtained and from plots similar to Fig. 4, the following relationships were obtained:

$$D_{v.5}^{-1} \sim W_g^{1.33} \tag{2}$$

$$D_{31}^{-1} \sim W_g^{1.33} \tag{3}$$

These results are in good agreement with atomization theory which predicts that the reciprocal characteristic dropsize, D_c, is directly proportional to the gas flowrate raised to the 1.33 power, for liquid jet breakup in the regime of aerodynamic-stripping, i.e., high velocity gasflow.

Effect of Nitrogen Gas Mass Velocity on Characteristic Dropsize

Values of the Sauter-mean, volume-median and volume-linear mean dropsizes were obtained at a gas flowrate of 4 g/sec and plotted against atomizer orifice area as shown in Fig. 5. The three plots have the same slope indicate that $D_c^{-1} \sim A_o^{-1.33}$ Since D_c^{-1} is also proportional to $W_g^{1.33}$, as shown by Eqs. (1) to (3), it is evident that

$$D_c^{-1} \sim (W_g/A_o)^{1.33} \tag{4}$$

which may be rewritten in terms of mass flux as follows:

$$D_c^{-1} \sim (\rho_g V_g)^{1.33} \tag{5}$$

Here it should be noted that the open area of the nozzle orifice as encountered by the gas phase is reduced due to blockage by the liquid droplets formed inside the atomizer and accelerating through the nozzle orifice.

In Fig. 6(a), values of D_{32}^{-1} are plotted against nitrogen mass flux and the following expression is obtained for the Sauter-mean diameter:

$$D_{32}^{-1} = 11.7(W_g/A_o)^{1.33} \tag{6}$$

In Fig. 6(b), a similar expression is obtained for the volume-median diameter:

$$D_{v.5}^{-1} = 8.9(W_g/A_o)^{1.33} \tag{7}$$

Acoustic Mass-Flux Effect on Dropsize

It is very difficult to measure gas and liquid velocities inside a two-fluid atomizer. Such data are needed in order to determine the gas velocity relative to liquid surface velocity, V_r, in the dimensionless force ratio defined as follows:

$$WeRe = D_o^2 \rho_g^2 V_r^3/\mu_l \sigma \tag{8}$$

If the product of the Weber and Reynolds numbers, WeRe, is multiplied by the density ratio, ρ_g/ρ_l, and it is assumed that the acoustic gas-flux, V_c, may be substituted for the relative velocity, V_r, since the liquid velocity is negligible compared with V_c, Eq. (8) may be rewritten as:

$$D_o^2(\rho_g V_c)^3/\rho_l \mu_l \sigma = (\rho_g/\rho_l)WeRe \tag{9}$$

Acoustic mass-flux is assumed equal to W_g/A_o, which is the quantity measured in the present study.

In Fig. 7, values of the dimensionless ratio, D_o/D_{32} are plotted against the product of fluid density ratio, ρ_g/ρ_l, and dimensionless force ratio WeRe. The slope of this plot gives the exponent 0.44 and the following expression is obtained:

$$D_o/D_{32} \sim \left[(\rho_g/\rho_l)WeRe\right]^{0.44} \tag{10}$$

From this expression, it is evident that: $D_{32} \sim V_c^{-1.33}$. This relationship between Sauter-mean diameter and acoustic gas-flux agrees very well with atomization theory,[9] for liquid jet breakup in the aerodynamic-stripping regime, i.e., at Mach 1 gasflow, as shown in Table I. Also shown in Table I are the results of other investigators who have also evaluated the exponent n, in the following expression for characteristic dropsize: $D_c \sim V_r^n$, or V_c^n.

The relationship given in Eq. (10) is plotted in Fig. 8 and the following expression is derived for liquid jet breakup at Mach 1 gasflow in pneumatic two-fluid atomizers:

$$D_o/D_{32} = 8.0\left[(\rho_g/\rho_l)WeRe\right]^{0.44} \tag{11}$$

which also agrees well with atomization theory for liquid-jet atomization in high velocity gas streams. A similar expression for the volume-median drop diameter, $D_{v.5}$, was obtained as follows:

$$D_o/D_{v.5} = 6.1\left[(\rho_g/\rho_l)\right]^{0.44} \tag{12}$$

Characteristic Exponents for Drop-Size Distribution Expressions

With the scattered-light scanner, experimental data were obtained for the exponent N_r, which appears in the Rosin-Rammler dropsize distribution expression as follows:

$$\frac{dv}{dx} = \frac{N_r x^{N_r - 1}}{c^{N_r}} e^{-(x/c)^{N_r}}$$

Experimental data were also obtained for the exponent N_n, which appears in the Nukiyama-Tanasawa expression as follows:

$$\frac{dv}{dx} = \frac{b^{6/N_n}}{\Gamma(6/N_n)} x^5 e^{-bx^{N_n}}$$

From a plot of the data obtained with the four atomizers, as shown in Fig. 9, the following relation was determined:

$$N_r = 2.8\ N_n^{0.45}$$

which is the same as that derived in Ref. 6. Thus, it was found that experimental values of exponents N_n and N_r for the two dropsize distribution expressions were not appreciably affected when atomizer orifice area was varied from 0.0804 to 0.2463 cm^2.

Concluding Remarks

Characteristic dropsize produced with four differently sized pneumatic two-fluid atomizers were measured with a scattered-light scanning instrument at a distance of 2.2 cm downstream of the nozzle orifice. As a result, a correlation of characteristic dropsize with dimensionless force ratios, i.e., Weber and Reynolds numbers, was obtained for liquid jet breakup in Mach 1 gasflow. The expression obtained for the Sauter mean, D_{32}, and volume median, $D_{v.5}$, drop diameters are as follows:

$D_o/D_{32} = 8\left[(\rho_g/\rho_l)WeRe\right]^{0.44}$ and $D_o\ D_{V.5} = 6.1$ $\left[(\rho_g/\rho_l)WeRe\right]^{0.44}$, where the dimensionless groups in the brackets may be defined as follows:

$(\rho_g/\rho_l)WeRe = D_o^2\ (\rho_g V_c^3)/\rho_l \mu_l \sigma$. In this expression, $\rho_g V_c$ is the acoustic mass-velocity of the gas phase and is equal to the weight flow of nitrogen gas per unit area, W_g/A_o. Thus from the preceeding expression, it is evident that: $D_{32} \sim (\rho_g V_c)^{-1.33}$. The exponent, -1.33 is in good agreement with atomization theory for liquid jet breakup in the aerodynamic-stripping regime at Mach 1 gasflow.

The experimental values of the exponents N_n and N_r for the Nukiyama-Tanasawa and Rosin-Rammler dropsize distribution expressions, respectively, were not appreciably affected as atomizer orifice diameter was varied from 0.32 to 0.56 cm.

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TABLE I. - VELOCITY EXPONENT, n, FOR ACCELERATION-WAVE BREAKUP OF LIQUID JETS: $D_c^{-1} \sim V_g^n$

Source	Exponent n
Theory[b]	1.33
Present study, $\bar{x}$ = 2.2 cm	1.33
Weiss and Worsham[c]	[a]1.33
Wolfe and Anderson[d]	1.33
Kim and Marshall[e]	[a]1.14
Nukiyama and Tanasawa,[f] $\bar{x}$ = 5 to 25 cm	1.0
Lorenzetto and Lefebvre[g]	1.0

[a]Drop-size data for wax spheres.
[b]Ref. 9.
[c]Ref. 4.
[d]Ref. 5.
[e]Ref. 1.
[f]Ref. 3.
[g]Ref. 2.

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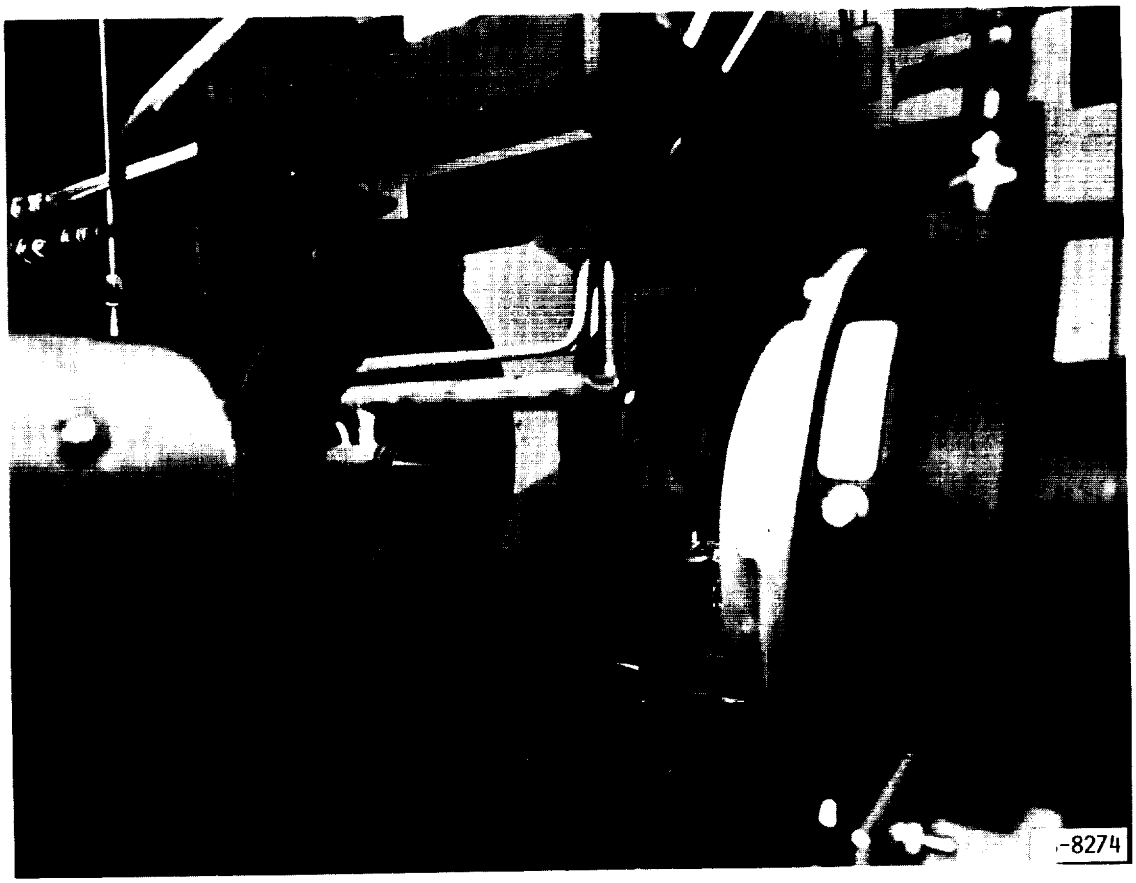


FIGURE 1. - APPARATUS AND AUXILLIARY EQUIPMENT.

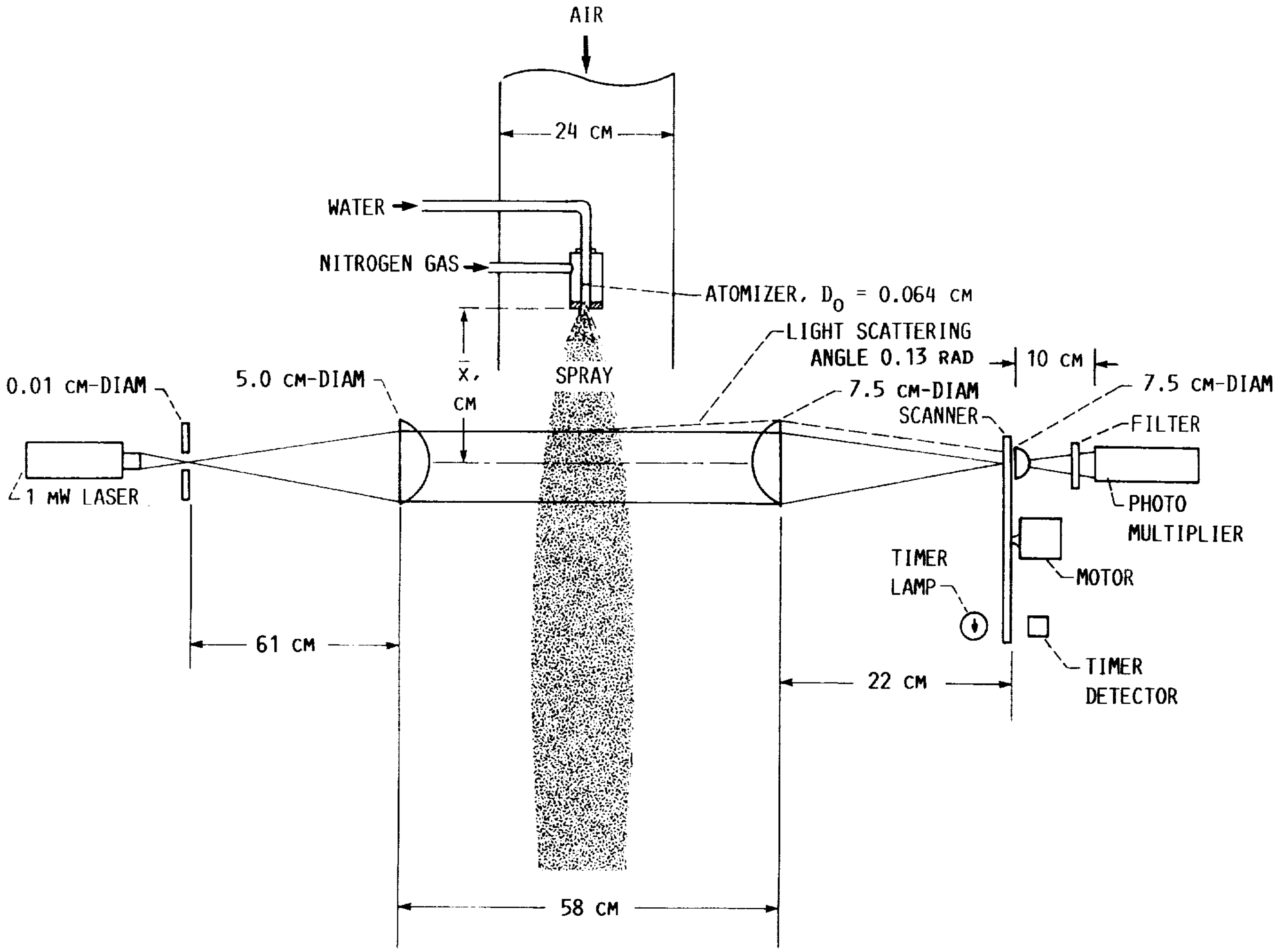


FIGURE 2. - ATMOSPHERIC PRESSURE TEST SECTION AND OPTICAL PATH OF SCATTERED-LIGHT SCANNER.

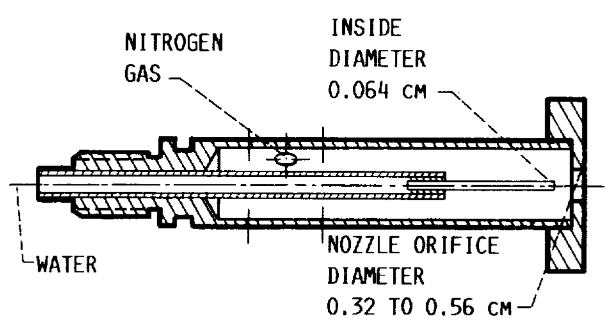


FIGURE 3. - DIAGRAM OF PNEUMATIC TWO-FLUID ATOMIZER.

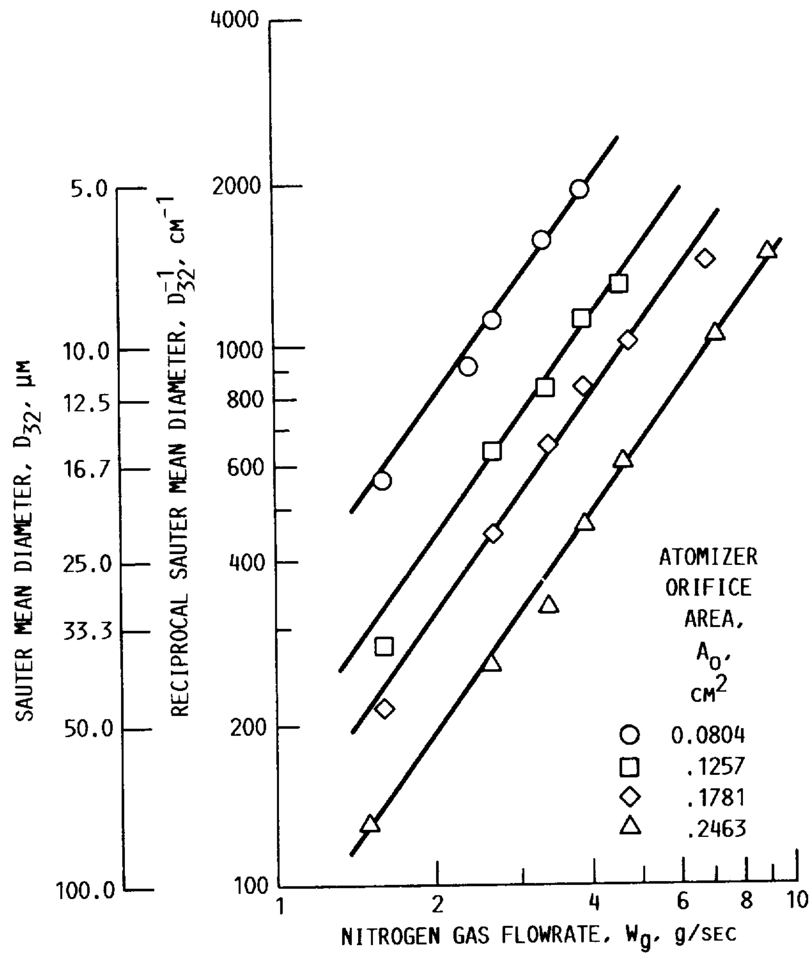


FIGURE 4. - VARIATION OF SAUTER MEAN DIAMETER, D_{32}, WITH NITROGEN GAS FLOWRATE, W_g, AT $x = 2.2$ CM AND $W_1 = 3.15$ g/SEC.

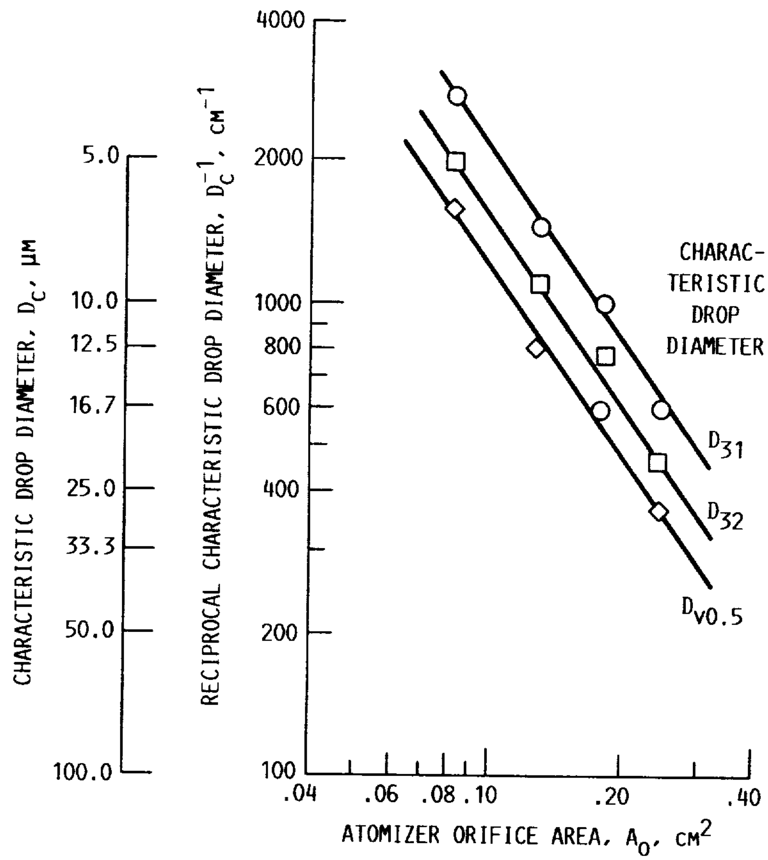
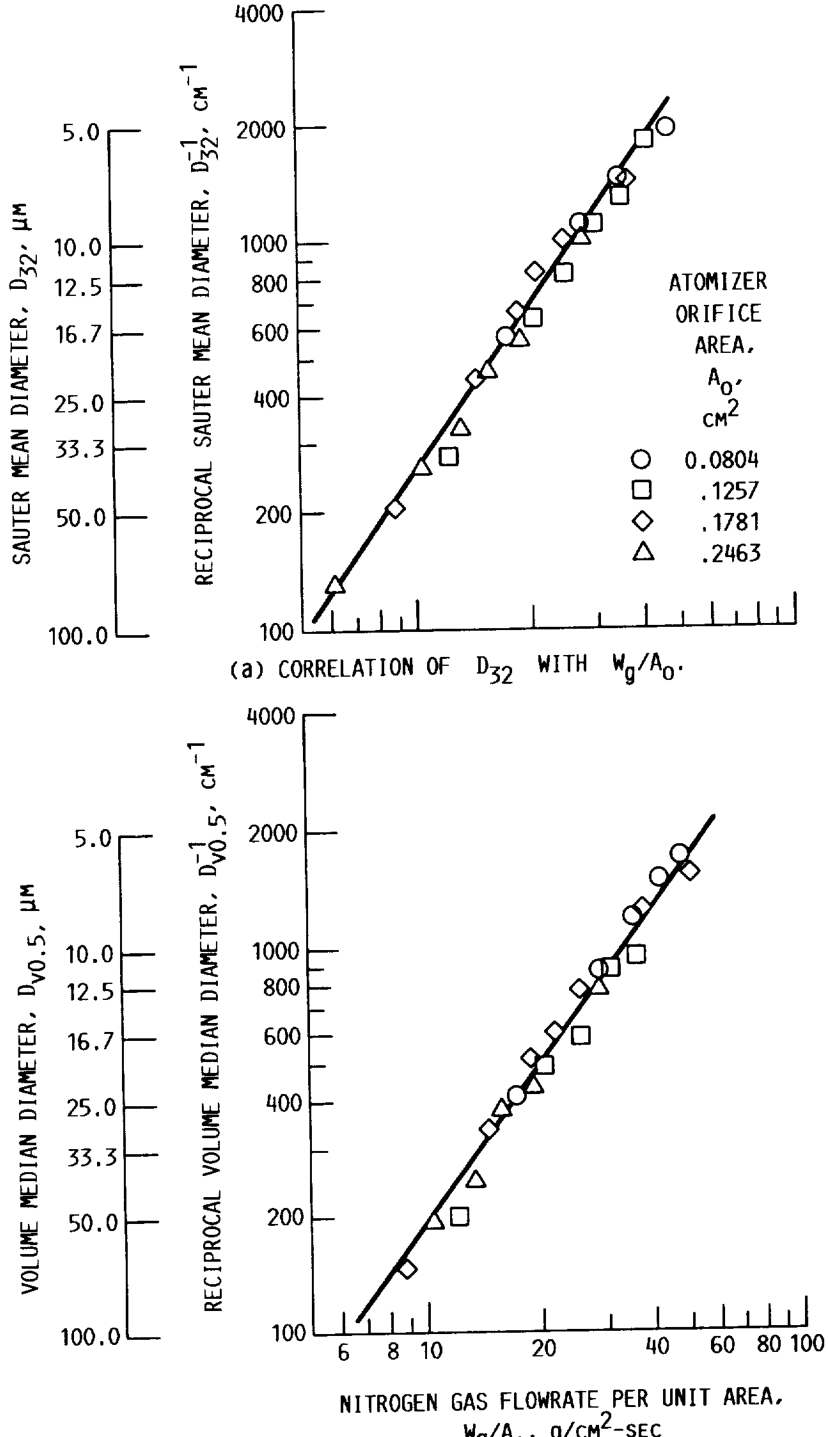


FIGURE 5. - VARIATION OF CHARACTERISTIC DROP DIAMETER, D_c, WITH ATOMIZER ORIFICE AREA, A_o, At W_g = 4 g/SEC.



(b) CORRELATION OF $D_{V0.5}$ WITH W_g/A_0.

FIGURE 6. - EFFECT OF GAS MASS-FLUX ON SAUTER-MEAN AND VOLUME-MEDIAN DROPSIZES.

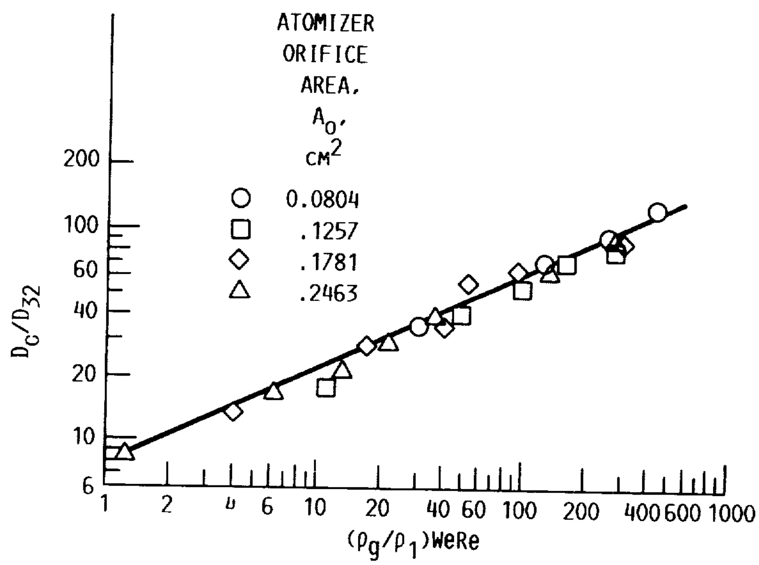


FIGURE 7. - VARIATION OF D_0/D_{32} WITH PRODUCT OF DIMENSIONLESS GROUPS (ρ_g/ρ_1)WeRe.

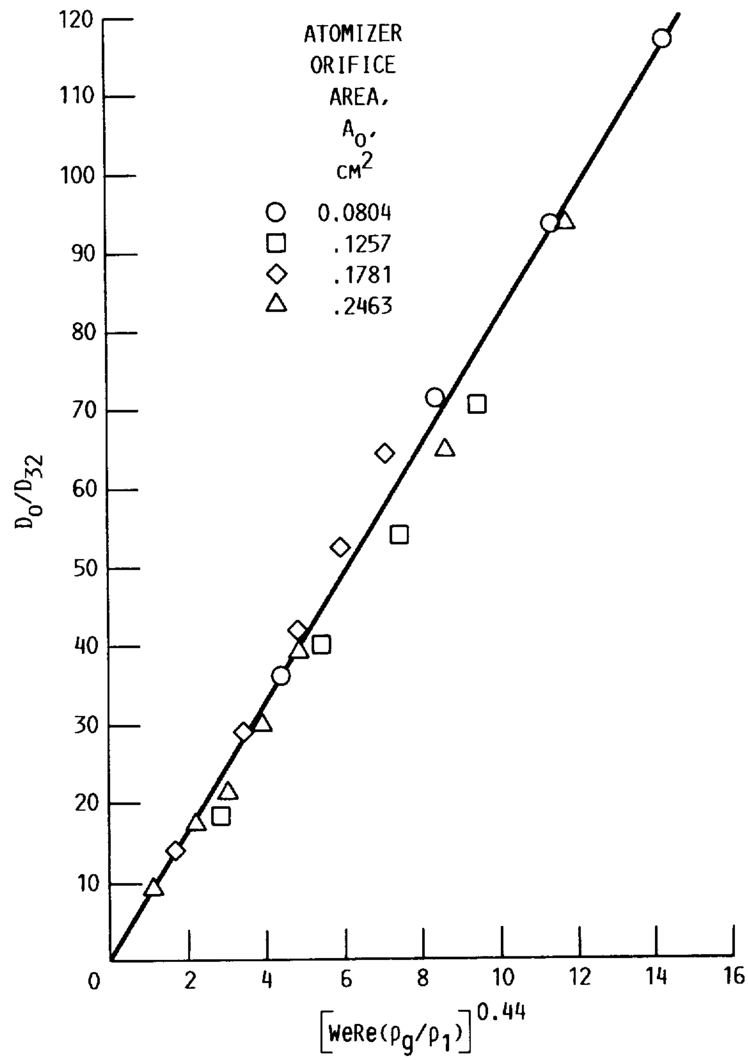


FIGURE 8. - CORRELATION OF SAUTER MEAN DIAMETER WITH REYNOLDS NUMBER, WEBER NUMBER, AND FLUID-DENSITY RATIO.

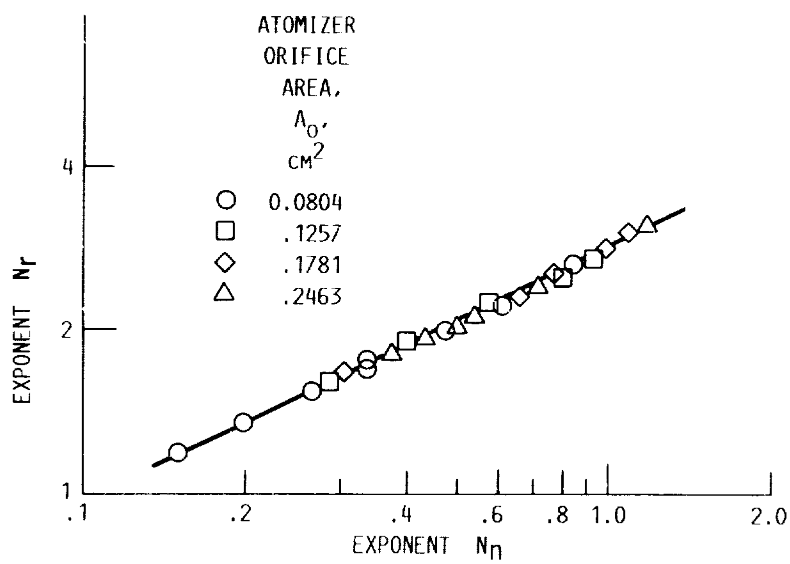


FIGURE 9. - CORRELATION OF ROSIN-RAMMLER AND NUKIYAMA-TANASAWA EXPONENTS N_r AND N_n, RESPECTIVELY.

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16. Abstract

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$$D_o/D_{32} = 8\ [(\rho_g/\rho_1)\mathrm{We\ Re}]^{0.44}$$

From this expression, it is evident that $D_{32} \sim V_c^{-1.33}$ which agrees very well with atomization theory for the case of acceleration-wave breakup of liquid jets.

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